Steady state and dynamic hygrothermal performance of rendered straw bale walls

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Key words: Straw bale; Building; Moisture; Hygrothermal

Abstract

Wheat straw, in the form of compacted bales, is increasingly used as thermal insulation in the external walls of buildings. Common practice is to use a render finish, applied directly to surface of the straw bales, to protect them from decay, and enhance structural performance and fire resistance. Coatings are typically made of water vapour permeable materials, such as lime or earth-based renders. Such coatings should allow water vapour to diffuse through, minimising the risk of liquid moisture build up within the thickness of the wall, reducing likelihood of decay. However, to date there has been very limited scientific study of this behaviour in rendered straw bale walls. The aim of the work presented in this paper was to develop understanding of the hygrothermal performance of lime rendered wheat straw bales. A test panel was subjected to varying environmental conditions, including a thermal shock, dynamic freeze−thaw exposure and hot humid conditions. Key scientific contributions of this

work include data on the dynamic and steady-state hygrothermal characteristics wheat straw bale walls, combined with the application of heat and moisture modelling. This work will further support uptake of straw bale construction by designers and their wider use in energy-efficient construction projects.

1. Introduction

Cellulose based insulation materials, such as cereal straw, hemp, flax and wood fibre, reduce the total carbon impact of building projects by both reducing energy requirements in use and reducing net carbon emissions in manufacture (Sodagar et al, 2011). The photosynthetic carbon stored in plant based materials means such materials are very effective carbon stores throughout their in-service lifetime. In recent years the need to find more sustainable alternative materials and to lower the carbon footprint of buildings has supported greater use of agricultural crop based materials, such as hemp and wheat straw (Minke and Mahlke, 2005). However, bio-based insulation materials generally require a form of wall construction which allows water vapour to diffuse through the full thickness of the wall, avoiding excessive moisture build up over time that could potentially lead to the decay of bio-materials.

Rendered straw bale walls may be considered a simple form of sandwich panel, with two outer skins of lime render applied directly onto the internal straw insulation. These walls lack a cavity, and their long-term performance has been viewed with caution by designers, regulatory and certifying bodies in particular (McLeod and Hopfe, 2013). Part of the concern surrounding the omission of wall cavities is the risk, perceived or otherwise, associated with the ingress of water or accumulation of condensation within the construction build up. In the past poor building practice and envelope design has led to significant high profile failures in buildings with no vented cavity and this serves to increase the perception of risk (Lawton, 1999). Nonetheless, new design standards and the tightening of building regulations to drive thermal efficiency improvements in the built environment has led to the rapid development of new wall construction methods for timber frame and more traditional brick and block construction. The high thermal insulation requirements of the Passivhaus design standard (www.passivhaus.org.uk) has led to an increased adoption of fully filled cavity construction in order to limit the thickness of these super insulated walls and to minimise the thermal losses through thermal bypass. New analysis tools for assessing the dynamic Heat & Moisture or hygrothermal performance of building fabrics, coupled with improved understanding of moisture management within building fabrics, has helped to facilitate this innovation whilst also providing a level of assurance to stakeholders involved with such buildings. One such tool is WUFI (Wärme Und Feuchte Instationär), which was developed by the Fraunhofer Institute for Building Physics in Germany (Künzel and Zirkelbach, 2013)

The movement towards full thickness wall insulation is an important development in the built environment and signifies a step change in building for optimum thermal efficiency (Bonnett et al, 2008). However, this form of construction requires deeper understanding of the hygrothermal performance of a wall to ensure that concerns about moisture accumulation are not a risk to longer term integrity and performance (Goodhew et al., 2004). In directly rendered straw bale wall panels the render surface is porous and the straw is hygric, therefore condensation in the form of liquid water is unlikely. However, straw moisture content will be higher in relation to high relative humidity and appropriate design or monitoring can be used to demonstrate that moisture content remains within serviceable limits (Carfrae et al., 2011).

The key to the successful in-service performance of directly rendered insulation systems, such as straw bale construction, is this appropriate understanding and use of vapour permeable finishes. In the UK, wall finishes should aim to maximise the vapour permeability of external finishes whilst limiting the potential for water absorption that could affect the substrate behind. In locations subject to extreme wind driven rainfall this may prove difficult and in this instance a rain-screen cladding may be required to minimise the direct wetting of a wall finish (Wihan, 2007).

The use of vapour permeable construction, comprising both vapour permeable coatings and insulation in the case of straw bale, creates dynamic hygrothermal conditions within the wall. In a climate with large diurnal, and annual, changes in temperature and humidity, the moisture content and distribution within the wall will mostly be in a state of flux. Equally in a predominantly warm and humid environment the bulk moisture content of a vapour permeable wall will likely be greater than that in a dry, arid region. The result is that consideration must be given to the hygrothermal performance of a building fabric when used in a particular climate. The same is true of conventional vapour closed building fabrics where the incorrect positioning or use of a vapour barrier can cause serious condensation build up to occur.

This paper presents findings from a laboratory study of the hygrothermal performance of rendered straw bale wall construction. The aim of the study was to develop empirically better understanding of straw bale wall performance, in simulated extreme environments, subject to range of steady state and dynamic hygrothermal conditions and to validate performance using modelling. To achieve this the straw bale test panel was sandwiched between two environmental chambers. In this study test panels are uniquely subject to cyclic conditions as well as to a steady state cold thermal shock. Results of the monitoring and the analysis provide new insight into the dynamics of moisture and heat flow within a rendered straw bale wall when drying following the application of render and then when subjected to extreme climatic excitation profiles. Exposure of the panel to an extreme heat-cold cycle demonstrated suitability of hygrothermal modelling to simulate performance of rendered straw bale walls with some confidence.

2 Summary of previous studies

There have been relatively few past scientific studies on hygrothermal performance of straw bale walls. Previous studies have presented either findings from long-term monitoring of buildings or test panels subject to steady state warm thermal shocks. Holzhueter and Itonga (2010) present condition monitoring data recorded from sensors installed in a straw bale wall of a single storey building in Kyoto Prefecture, Japan. Seasonally, Japan has a hot and humid climate. They reported a mean average external temperature and relative humidity of 26C and 80% respectively during the summer month of August. Conversely the mean average temperature drops to 4C during January. The monitoring data highlighted that the hygrothermal conditions within a vapour permeable (and hygroscopic) wall can vary significantly. During the winter months the highest levels of interstitial moisture are reported to be in the straw behind the external (cold) face of the wall whilst in the summer the opposite is true.

Dubois et al (2016) presented results from an experimental study combined with Heat & Moisture modelling, using COMSOL (multi-physics modelling software), of a straw bale panel subject to a ‘steady state’ 15C warm thermal shock. One of the findings of their work concluded that a single constant temperature isotherm for the straw was not sufficient to accurately model the observed experimental performance.

The dynamic variation of moisture within a wall is sometimes considered to be a relatively passive occurrence with limited influence on the energy performance of buildings. However, the thermal conductivity and vapour permeability of hygroscopic insulation materials such as straw is dependent on its moisture content. Additionally heat is released and absorbed during condensation and evaporation of moisture. This will alter the temperature profile and saturation values within a wall, which in turn affects the amount of condensation and drying within the wall (BS EN ISO 13788, 2002). Dynamic hygrothermal response within a wall to varying external conditions has been reported by Evrard and De Herde (Evrard and De

Herde, 2010) and Lawrence et al. (2013) for wall panels constructed with hemp-lime composite material. Both studies explored the response of the wall panel when subjected to a sudden thermal shock and sought to compare this with an equivalent vapour closed wall assembly.

In the past vapour permeable construction has been considered a relatively isolated specialism of historic building experts. However, with the increased use, demand and low carbon potential of new bio based materials it is now timely for the hygrothermal performance of this form of construction to be understood in greater depth. Previous studies provide important findings and data from laboratory testing and in-situ monitoring of building fabrics (Dubois et al, 2016; Thomson and Walker, 2013; Thomson and Walker, 2014). However, the evidence base and understanding of the hygrothermal performance and characteristic behaviour of straw bale walls remains very limited. This study aims to fill-in some important gaps in performance through dynamic testing and simulation of performance.

3. Materials and methodology

3.1 Test panel fabrication

A small scale panel test specimen was constructed using an 18 mm thick plywood frame which was insulated around the internal perimeter with 50 mm thick rigid foam insulation to minimise edge effects on the temperature and relative humidity conditions (Figure 1). The external dimensions of the plywood frame were 750 mm wide x 550 mm high x 460 mm deep and this was selected in order to fit the aperture of the environmental chambers and the typical 400 mm depth of a straw bale with 30 mm of lime based render applied to both sides.

Figure 1. Fabrication of straw bale test panel

The straw bale infill was formed from a single wheat straw bale that was sub-divided in order to fit the internal dimensions of the test panel. The straw was installed at a bulk density of 97 kg/m^3 and had a bulk moisture content of approximately 12% on a dry mass basis. The straw was trimmed to provide a flat surface for application of the render to either side of the panel. In Figure 1 shows the straw and insulation recessed back from the front of the plywood frame, which allowed the thickness of the render to be controlled as well as facilitating its application. The panel was rendered in two stages using a highly vapour permeable formulated lime render (Baumit K39) widely used for both straw bale and hemp-lime. The second render coat was applied to the keyed first coat after a seven day curing period. The final coat of render was allowed a further 25 days to cure prior to installation of the panel between the environmental chambers.

3.2 Test setup

To measure the hygrothermal performance of the panel it was sandwiched between two TAS environmental test chambers (Figure 2). To minimise edge effect heat losses a second layer of rigid insulation was wrapped around the outside of the test panel. The doors of each chamber were removed. A rubber gasket around the opening ensured a tight seal was provided around the edges of the panel on both sides.

Figure 2. Panel installed between chambers

The straw bale test panel was subject to the following test regimes. The ambient reference conditions of 20C/50% RH were chosen in accordance with the baseline constant internal conditions set out in BS EN 13788 (2002):

- Panel drying: Both sides of the panel were held in steady state conditions for a period of 31 days at 20C/50%RH in the test chambers.
- Cold thermal shock: Following steady state conditioning for 31 days at 20C/50%RH, the warm side was maintained at 20C/50% RH, the cold side reduced to 2.5C/65% RH for 10 days.
- Extreme heat-cold cycles: After returning to ambient steady state conditions (20C/50%RH), one side of the panel was subject to five heat-cold 24 hour cycles of 50C for a total of 8 hours (rising over 1 hour) followed by exposure to -20C for a total of 16 hours (falling for 2 hours).
- Hot humid conditions: After returning to ambient steady state conditions (20C/50%RH), one side of the panel was held at 20C/50%RH whilst on the other side the conditions were held constant at 35C/95%RH for 24 days.

The conditions within the chambers were monitored to confirm the accuracy of the conditions within them. The stability of the chambers is stated by the manufacturer as ± 1C and ± 3% relative humidity. When set to 20C/50% RH, a 14-day period of monitoring showed that the average temperature in the two chambers was 20.9C and 20.8C and relative humidity was 52.6% and 51.0%. For the period monitored, the data showed high consistency in performance of the chambers. It is acknowledged that the sensors themselves will have limitations to their accuracy, but they serve as a robust indication of the reliability of the environmental chambers and the data presented in this paper.

3.3 Instrumentation

Relative humidity and temperature were monitored within the panel using Humirel HTM1735 sensors. Bespoke clear acrylic covers were laser cut to provide protection to the sensors when installed in the panel and to ensure robust connection of the wires. Data readings from the sensors were recorded using two Grant Instruments Squirrel 1000 series data loggers. Three sensors were installed in the centre of the panel in the locations shown in Figure 3 and a further sensor was positioned externally on the top of the panel to record external ambient conditions surrounding it. The outermost sensors were positioned to minimise the risk of exposure to lime render upon application.

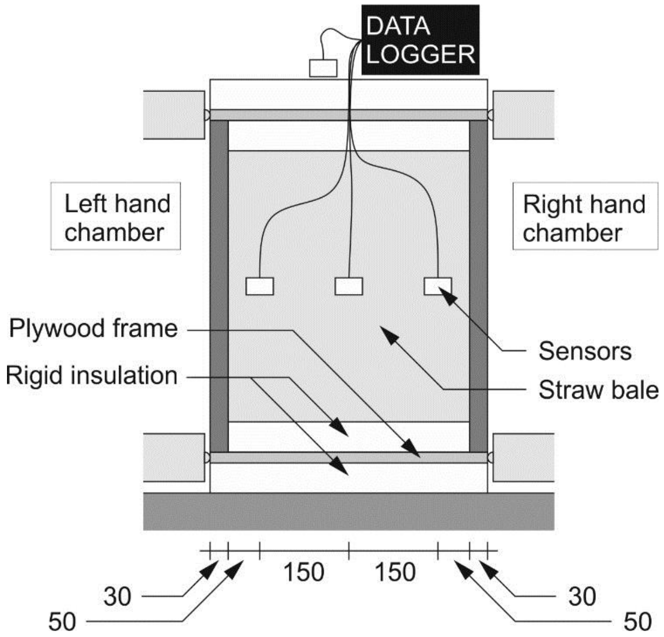

Figure 3. Test setup for hygrothermal panel test

3.4 WUFI simulation

Analysis of the straw bale panel was completed using the hygrothermal analysis software WUFI PRO 5.2. The objective for running simulations of the panels was to understand whether the software could be considered suitable for the prediction of moisture and heat flow across the panel and to validate published material properties for straw bale insulation. Material property data for the WUFI model were taken from a number of sources. Dubois et al (2016), Evrard and De Herde (2010) and Wihan (2007) present straw material properties used in analytical studies of different straw bale wall constructions. Dubois et al (2016) used a COMSOL Heat & Moisture model, whilst Evrard et al (2012) and Wihan (2007) used WUFI software to complete the analysis. Shea et al (2013) applied a least squares regression model to determine the thermal conductivity of wheat straw bales. These were based on guarded hotbox tests and published literature. The result provides a thermal conductivity value of 0.064 W/m·K for straw bales used in building construction. This value is therefore used for the WUFI analysis presented in this paper. The properties for the lime based render were based upon a standard render in the WUFI materials database except where manufacturer's material data was available.

Table 1. Principal hygrothermal properties of materials used in WUFI analysis

Property	Units	Straw	Lime render
Density	kg/m^3	97	1600
Porosity	%	0.9	0.3
Heat Capacity	J/kgK	2000	850
Thermal conductivity	W/m^2K	0.064	0.93
Vapour diffusion coefficient, μ	N/A	1	10

The WUFI simulations were run for each of the three climate profiles. For each climate profile the relative humidity and temperature profiles within the environmental chambers were recorded. These data were used to create WUFI climate files for the internal and external climates used in each simulation. By using the recorded excitation profiles a more accurate simulation could be completed and an even more developed understanding of the reliability of WUFI software to analyse straw bale construction evaluated.

4. Results and discussion

4.1 Panel drying behaviour

After being rendered the straw bale panel was stored under ambient laboratory conditions for 32 days prior to installation between the environmental test chambers. This allowed the drying characteristics of the panel to be observed whilst also allowing the render sufficient time to cure before moving. Figure 4 shows the monitoring data recorded during the drying of the panel, and before being installed between the environmental chambers at which point conditioning of the panel and accelerated drying through dehumidification began (Figure 5). Relative humidity and temperature monitoring commenced from the time that the first scratch coat of render was applied to the straw and this is shown as day zero in Figure 4. On day seven the second render coat was applied to the panel. Prior to this coat being applied it can be seen in Figure 4 that there was a slight decrease in relative humidity within the panel. After the second coat of render was applied the relative humidity begins to rise again and there is a drop in temperature within the panel. This drop in temperature may be attributed to the relative lower temperature of the wet render when it was applied and subsequent evaporation of water vapour from its surface.

At the start of this first period of monitoring the relative humidity and temperature in the panel is at a relatively consistent level through the depth of the straw. Following the application of the first coat of render the relative humidity local to the straw behind the render rose quickly, whilst the centre sensor recorded a constant relative humidity for approximately three days before rising at the same rate for approximately 10 days. During this period the temperature through the panel and in the space in which it was stored is moderately steady at approximately 20C. Therefore the rise in relative humidity can be attributed to wetting as a result of moisture from the render being both absorbed and adsorbed by the straw. The straw begins to dry at the outer faces of the panel 13 days after the first coat of render was applied. This can be seen from the gradual decrease in relative humidity recorded at these locations. However, the flow of moisture towards the centre of the panel does not reverse for a further 10 days after which there is evidence of drying across the full thickness of the straw bale.

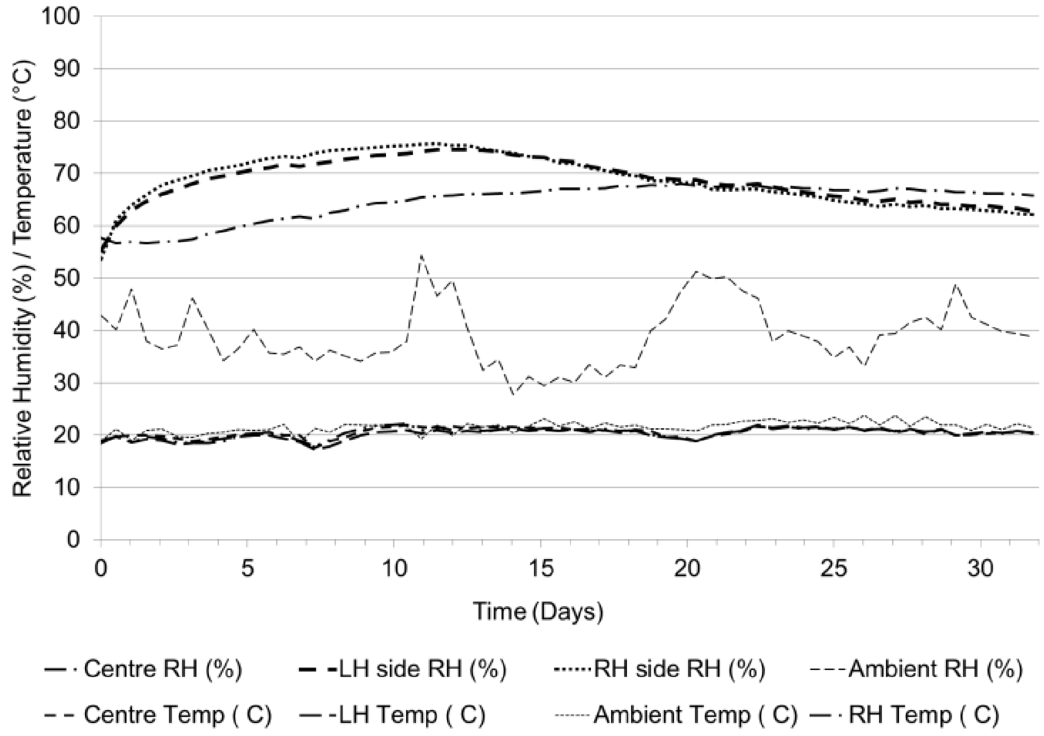

Figure 4: Initial drying response of panel in ambient conditions

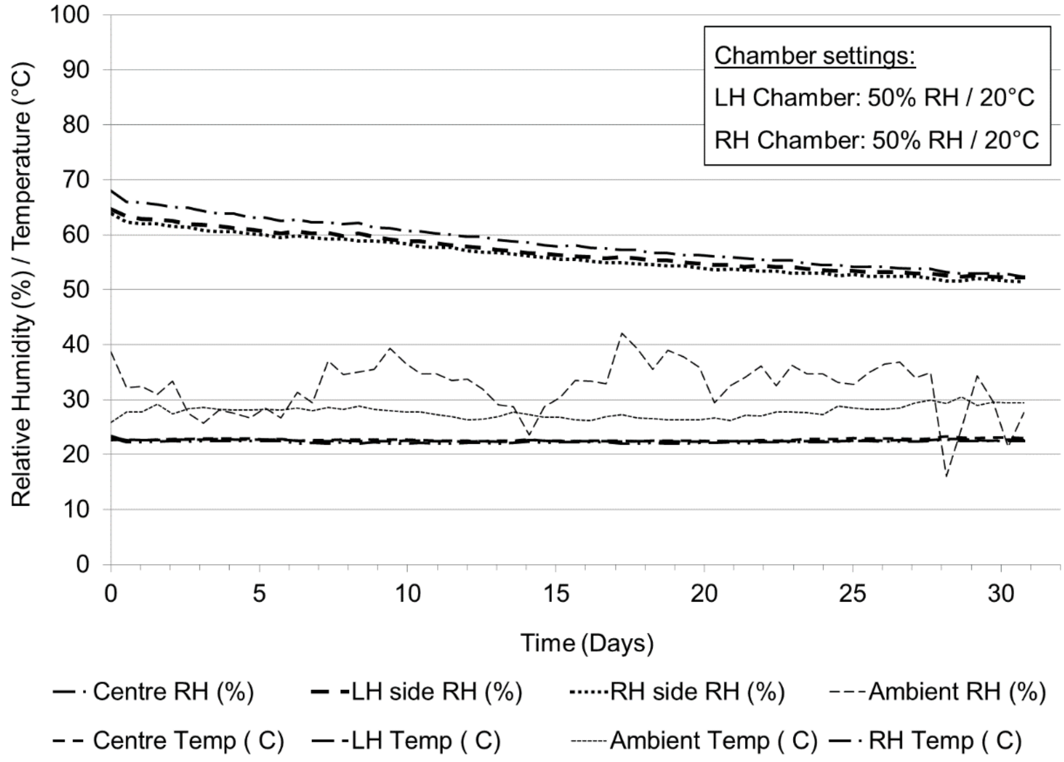

Figure 5: Accelerated drying response of panel

After the 32 day drying period under ambient conditions the panel was subjected to an accelerated period of drying through conditioning with the environmental chambers. All of the hygrothermal profiles that the panel were subjected to were started from the same initial conditions of 50% relative humidity and 20°C. In total it took 31 days for the humidity conditions within the panel to reach an equilibrium consistent with the conditions of the chambers either side.

4.2 Cold thermal shock

This section presents monitoring data from a test investigate the response of the straw bale panel when subjected to a rapid cold thermal shock on one side whilst the other side was maintained at a constant ambient condition representative of internal room conditions. This gives an indication of how quickly a steady state heat flow is achieved when a wall is subjected to a sudden drop in external temperature. The rate at which the temperature profile reaches a steady state heat flow will influence the amount of energy transferred for a given period of cooling. For instance if two insulation materials with similar U-values were to be compared and one reached steady state heat flow in 12 hours while the other took 24 hours then the material with a slower response would typically transfer less energy when subjected to short term diurnal swings in temperature. The test also shows how the relative humidity within the straw insulation is affected if the temperature gradient is maintained.

The straw bale panel was found to reach steady state heat flow within 48 hours of being exposed to a sudden cold shock on one face. This was verified by running the test for 240 hours, at which point no further change in the temperature profile had been measured. By comparison Evrard and De Herde (2010) used the WUFI software to model different wall types when subjected to a sudden thermal shock the same as that used for the straw bale panel. They found that a 335 mm thick rendered hemp lime wall reached steady state in 68 hours and a 297 mm thickness mineral wool wall took 15 hours. The hygrothermal lag demonstrated by straw bale walls can help to reduce energy transfer when a wall is subjected to dynamic swings in external temperature.

The monitoring data for the cold shock test are presented in Figure 6. The WUFI analysis data are presented in Figure 7 for comparison. The monitoring results show that the cold shock causes an initial drop in relative humidity on the cold side of the straw bale. However, as the temperature profile reaches steady state the relative humidity begins to rise as water vapour transfers from the warm side of the panel. After 230 hours of steady state exposure the rate that the relative humidity is rising is slowing and therefore it is not expected to reach a level that would cause degradation under these steady state conditions (Thomson and Walker, 2013; Thomson and Walker, 2014). The WUFI analysis of the panel when subjected to a cold shock shows reliable trends when compared to the actual monitoring result. The main point of note is the difference in magnitude of the relative humidity. The WUFI analysis gives a lower level of relative humidity change than actually monitored though the general trends are very similar. There are many possible reasons for this, including sensor accuracy, modelling assumptions with the WUFI software and the material properties used for the panel. It is outside the scope of this paper to try and identify the source of this difference.

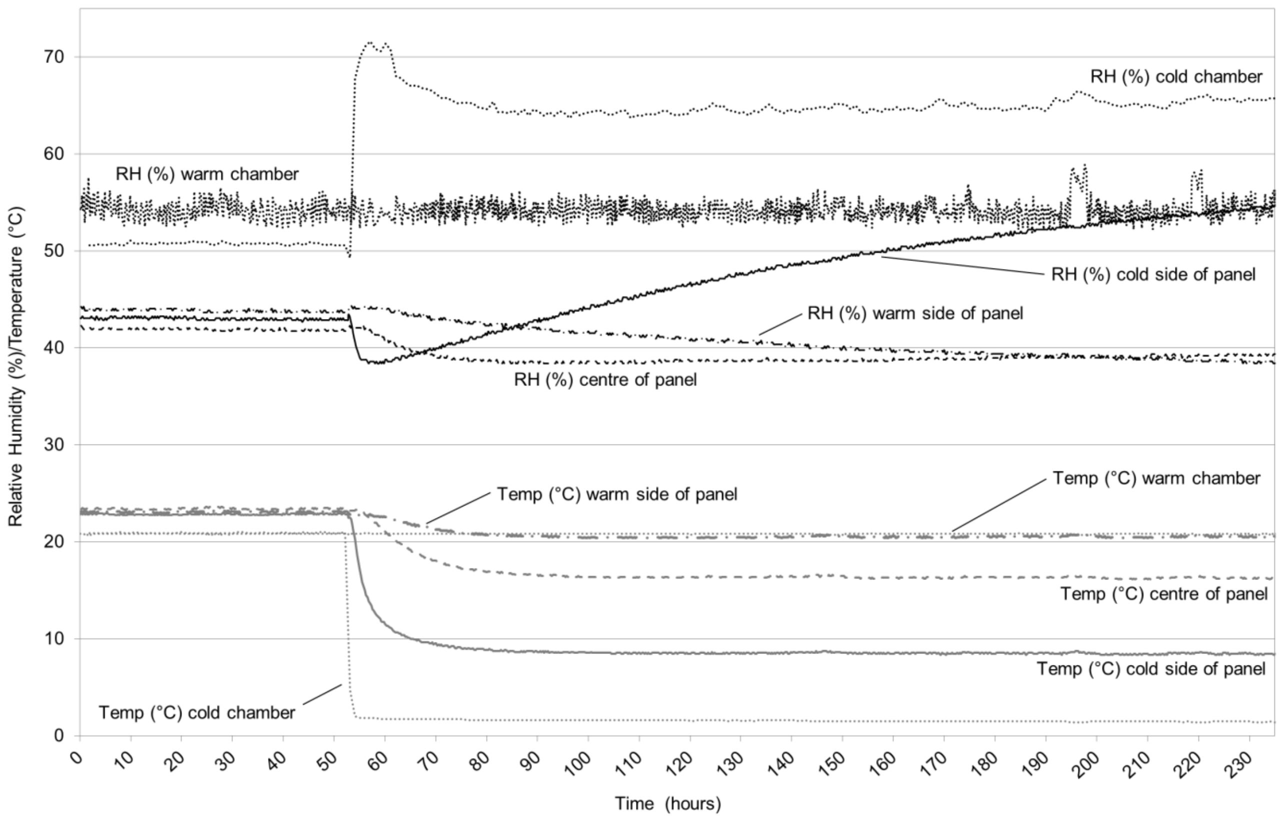

Figure 6: Recorded data from test panel following exposure to thermal shock

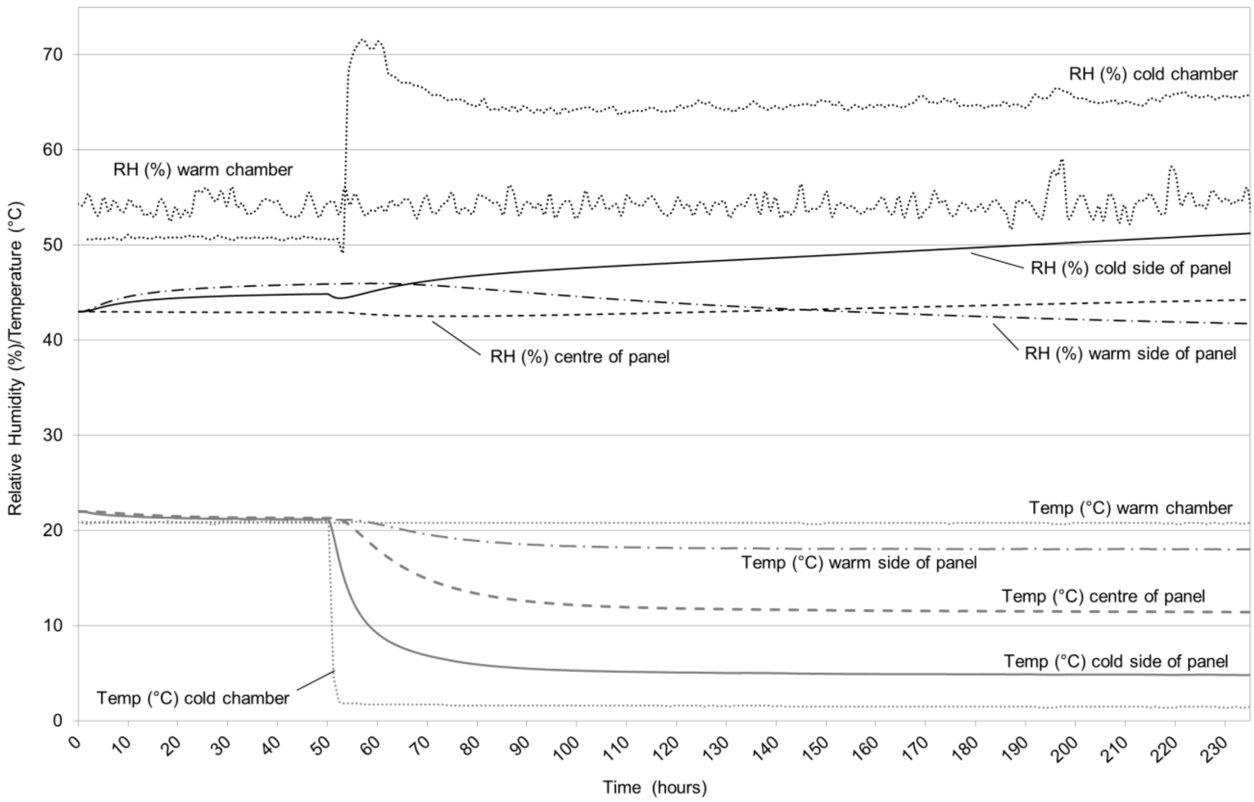

Figure 7: WUFI model response for test panel following exposure to thermal shock

4.3 Extreme heat-cold cycles

The second profile that the straw bale wall panel was exposed to was an extreme series of five heat-cold cycles. The excitation profile was based on the weathering profile set out in ETAG 004 (2011). This profile is made up of five heat-cold cycles of 24 hours comprising the following phases: exposure to 50C for a total of 8 hours (rise over 1 hour) followed by exposure to -20C for a total of 16 hours (fall for 2 hours). The relative humidity was uncontrolled in the excitation chamber for the duration of the exposure period. The other side of the wall panel was maintained at an ambient level. In this test the ambient conditions were set at 20ºC and 50% relative humidity as per the other two profiles. The aim of exposing the straw bale wall panel to this series of heat-cold cycles was firstly to understand the thermal lag through the thickness of the straw bale insulation and secondly to test the WUFI simulation under extreme exposure conditions.

The recorded temperature profiles through the thickness of the straw bale insulation are presented in Figure 8 alongside the relative humidity profiles. The WUFI analysis data are presented below in Figure 9. The first observation to note is that the temperature profile through the straw bale insulation does not reach steady state under the 8-hour heating or 16-hour cooling cycle. There is also evidence of a thermal lag through the thickness of the panel with the temperature at the unexposed side peaking several hours after the excitation profile changes. As with the cold shock test the relative humidity recorded at the exposed side of the panel rises when subjected to rapid heating and drops when exposed to rapid cooling. This may be attributed to rapid vapour flow away from and towards the back of relatively low permeability lime render on the exposed side of the panel. It is evident that after the initial rapid rise and fall of relative humidity a more conventional flow of moisture from high temperature to low begins as the temperature moves towards a steady state. This dynamic humidity change is validated with the WUFI analysis. Here the same temperature and humidity profiles are evident for the extreme heat-cold excitation profiles. However, as with the cold shock test the magnitude of the relative humidity analysis is notably lower than that recorded within the straw bale insulation.

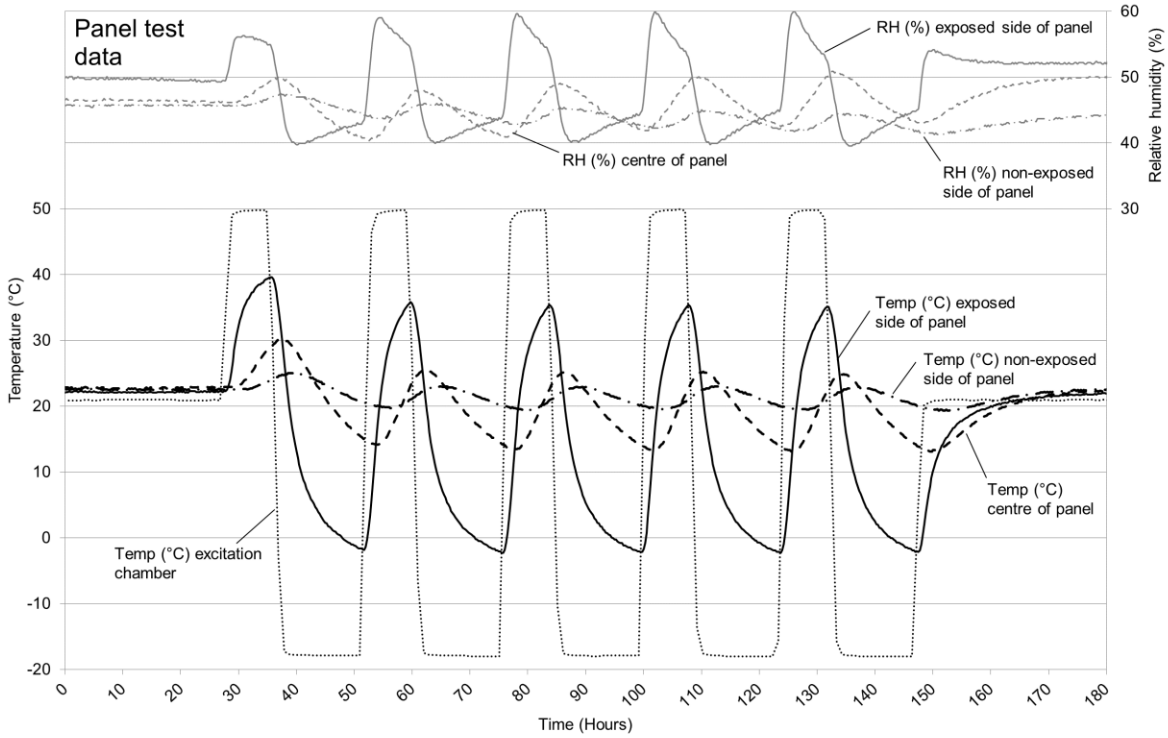

Figure 8: Recorded data from test panel following exposure to heat-cold cycles

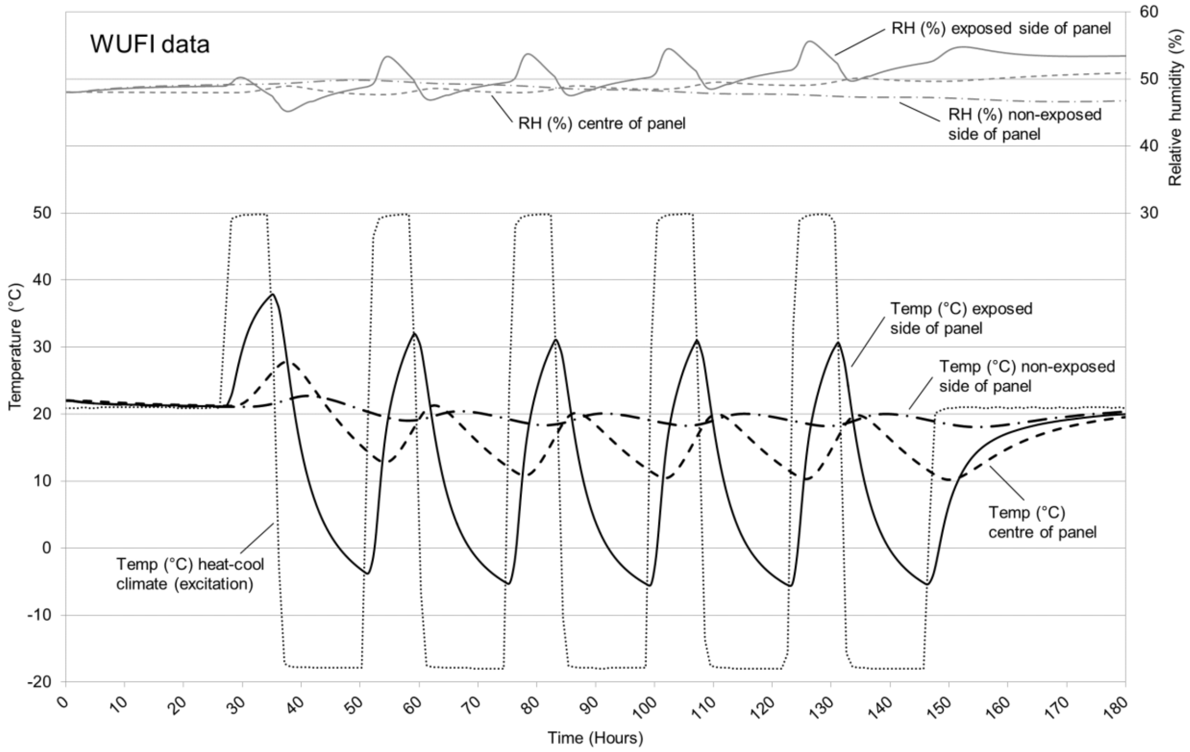

Figure 9: WUFI simulation output for test panel following exposure to heat-cold cycles

4.4 Hot humid conditions

The third conditioning profile focussed on another extreme climatic condition but instead of exposing the panel to relatively dry and cold conditions the ‘exterior’ conditions were this time selected to reflect a hot and humid environment. The other environmental chamber was maintained at the same ambient conditions as above (20C / 50% RH) to reflect those of an air conditioned internal space within a building. The important difference between this hot humid profile and the cold dry cycle is that the ambient conditions reflect two different situations in terms of internal space conditioning. The hot and humid configuration represents an air conditioned, cooled internal space, whilst the cold dry set up represents a heated internal space.

The monitoring data for the temperature and relative humidity within test panel are presented in Figure 10 alongside the data recorded in both of the environmental chambers. The hot and humid conditions were maintained at a constant level for 24 days. The temperature profile through the wall reaches steady state within 24 hours as for the cold shock test. Therefore running the profile for 24 days made it possible to see how the water vapour varies within the straw bale insulation as changes in relative humidity will be independent of temperature change during this period.

Prior to setting the environmental chamber to the hot and humid conditions both sides of the panel were pre-conditioned to the ambient 20C and 50% RH. At the point that the chamber moves towards the set conditions the relative humidity behind the exposed render shows an initial sharp increase before rising further at a more gentle and non-linear diminishing rate. However, whilst the rate of increase slowed during the exposure period the relative humidity on the exposed side did not reach equilibrium with the 'external' relative humidity of 95%. The relative humidity on the cooler 'internal' side of the straw bale shows a very interesting rise throughout the test as the rate at which it changes is faster than that on the warm humid side. This suggests that moisture is transferring from the warm humid 'external' side of the wall to the cooler 'internal' side from two sources. The first source of moisture is from within the straw itself and the second is the hot humid 'external' air permeating through the lime render. This result highlights the importance of identifying the dominant vapour flow direction in a wall build up as an incorrectly positioned vapour control layer could lead to serious damage. In this instance the build-up of moisture within the straw bale insulation on the cooler (20C) 'internal' side had caused some mould growth on the straw, which was identified when dismantling the panel after this test (Figure 11). No mould could be seen on the warm side of the straw.

The WUFI simulation results for this test series are presented below the monitored data plots in Figure 12. The software was unable to accurately simulate the conditions within the panel. Initially a much more rapid rise in relative humidity is observed in the WUFI model than recorded in the test panel. This relatively rapid rise continues for the first nine hours of exposure before the model becomes unstable and a rapid jump occurs in the relative humidity. Instability such as this is noted in the WUFI handbook as a limitation of the software when modelling hygrothermal materials at high levels of relative humidity. The results of the simulation represent an extreme case, which is unlikely to be encountered in real life. However, the results are presented here as they highlight the potential limitations of using hygrothermal modelling software for the analysis of straw bale wall insulation.

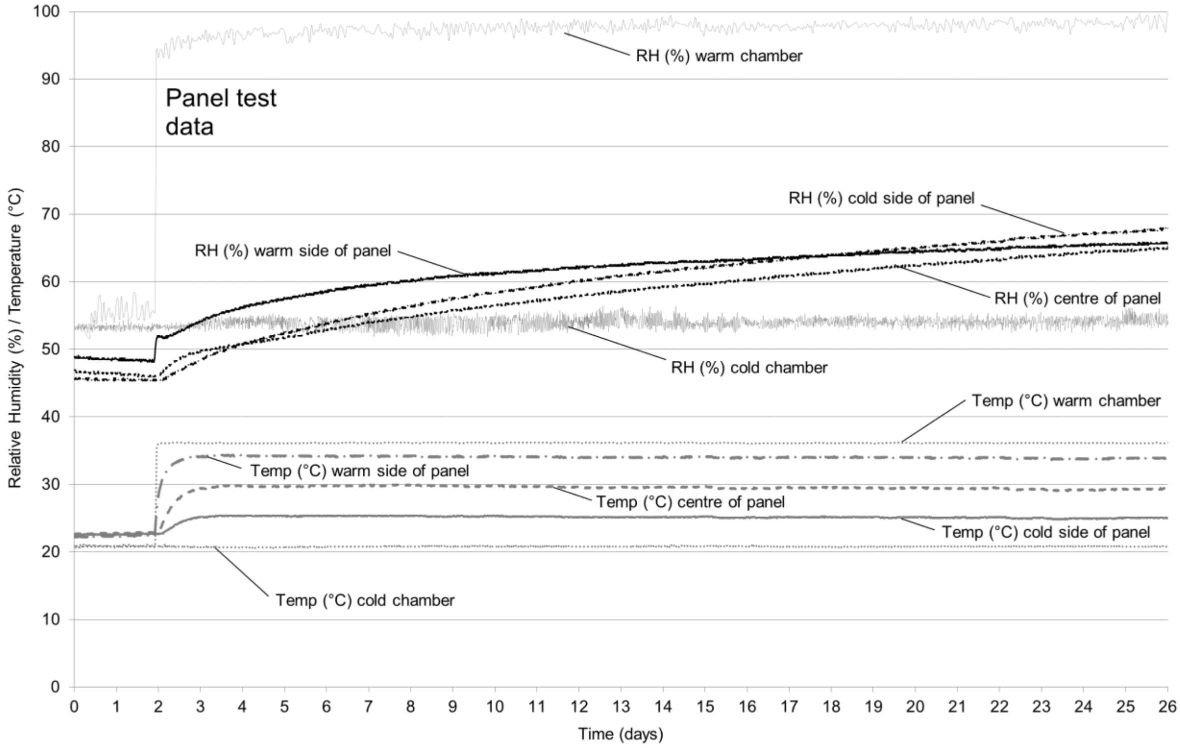

Figure 10: Recorded data from test panel following exposure to hot humid conditions

Figure 11 Evidence of mould growth on straw taken from test panel after testing

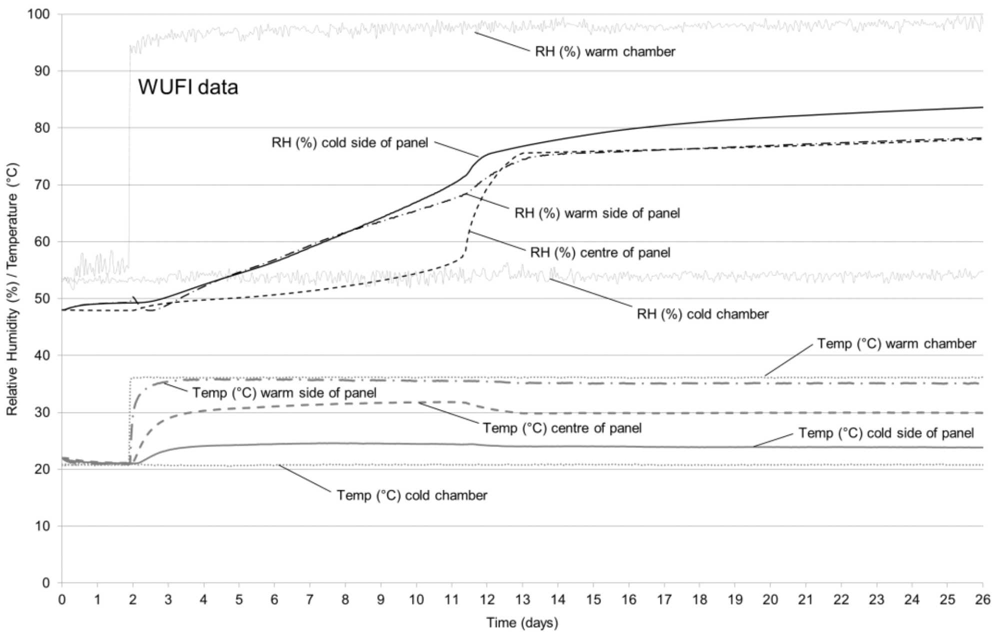

Figure 12: WUFI model simulations for test panel following exposure to hot humid conditions

5. Conclusions

This paper presents monitoring data and analysis results for a novel series of hygrothermal exposure tests on a rendered wheat straw bale wall panel, including tests under a variety of extreme environmental conditions. Overall this work has improved understanding on longer-term durability and performance of straw bale construction subject to a range of steady state and variable environmental conditions, improving confidence in this novel form of construction. Results of the monitoring and the analysis provide new insight into the dynamics of moisture and heat flow within a rendered straw bale wall when drying following the application of render and then when subjected to extreme climatic excitation profiles. When subjected to a rapid cold shock the insulation reached a steady state temperature profile within 24 hours, which is encouraging when considering heat loss on a diurnal cycle. Exposure of the panel to an extreme heat-cold cycle demonstrated the potential for hygrothermal modelling software such as WUFI to reliably model dynamic temperature and humidity changes within the straw bale insulation. Typically the software underestimated the internal panel relative humidity levels in extreme cases. Although some further refinement to the modelling, including improved understanding of input parameters, is required to improve correlation with measured performance, hygrothermal modelling can be used by designers to simulate performance of rendered straw bale walls with some confidence.

Exposure of the straw bale panel to extreme hot and humid climatic conditions showed that in an air-conditioned building there is a risk of elevated moisture content within the straw on the cool internal side of the wall. It is worth noting that this also has the potential to occur in conventional types of wall build up and is not a unique occurrence in directly rendered straw bale walls. Nonetheless, for moisture sensitive building materials such as timber or straw this should be avoided through appropriate design. In this paper, the extreme exposure conditions highlighted the potential for inwards vapour flow. If this is considered a risk in a particular climate then an appropriate use of vapour permeable materials should be adopted. The use of a lime plaster with a fine lime wash on the external face and a clay plaster on the internal face could be one such option.

Acknowledgements

This authors wish to acknowledge the support of colleagues in the Department of Architecture & Civil Engineering at the University of Bath, where the experimental work reported in this paper was completed.

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